The Kona Earthquake of August 21, 1951, and Its Aftershocks[1]

GORDON A. MACDONALD and CHESTER K. WENTWORTH[2]

INTRODUCTION

AT THREE MINUTES before one o'clock on the morning of August 21, 1951, the southwestern part of the island of Hawaii was shaken by the strongest earthquake recorded there since 1868. The earthquake of August 21 was felt strongly all over the island of Hawaii, weakly on the island of Maui, and in Honolulu, 180 miles away from its origin. Extensive damage resulted in the central Kona district, and lesser damage extended all the way to Naalehu, about 38 miles from the epicenter. The major earthquake was followed by a large number of aftershocks which, although they did little damage, kept the populace of Kona uneasy for several weeks.

A detailed study of the earthquake was immediately undertaken by the staff of the Hawaiian Volcano Observatory. No sharp division of labors existed, but for the most part Macdonald was responsible for the general and instrumental phases of the investigation and Wentworth for the detailed studies of damage, such as that affecting water tanks, stone walls, and gravestones.

Acknowledgements: It is impossible to mention by name all the persons who aided the investigation by contributing observations on the earthquake itself and data on resulting damage. To all these we extend our sincere thanks. Special thanks are due Howard M. Tatsuno, seismograph operator at Konawaena High School near the epicentral area; Sister Mary Thecla, seismograph operator at St. Joseph's School in Hilo; Mrs. Alfred E. Hansen at Naalehu, Allan P. Johnston of Kapapala, and Nancy R. Wallace of Kealakekua, who contributed descriptive reports of many of the aftershocks. Roland E. White, of the Honolulu Magnetic Observatory, U. S. Coast and Geodetic Survey, kindly sent copies of the seismograms of the major earthquake as recorded at Barbers Point, on Oahu. Commander C. A. George, of the Coast and Geodetic Survey, supplied copies of the tide gauge records from Honolulu and Hilo harbors, showing the small tsunami that followed the earthquake. Many persons supplied information on damaged water tanks. Among these Mark Sutherland, Principal of Konawaena School, John Iwane, Extension Service, University of Hawaii, and Masuoka Nagai, of Captain Cook Coffee Company, were especially helpful.

NARRATIVE

Most residents of the island of Hawaii were in bed when the earthquake struck. Nearly everyone in the Kona and Kau districts was awakened, and most people rushed outdoors. Persons in the area near the epicenter reported that the initial movement was largely up and down, with some swaying in an east-west direction, increasing in intensity and giving way to what appeared to be a vortical motion. Noise during the earthquake was intense as doors and windows rattled,

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[2] Director and Geologist, respectively, Hawaiian Volcano Observatory, Hawaii National Park, Hawaii.

dishes and furniture toppled to the floor, water tanks collapsed, and rocks rolled down from stone walls and banks. A few persons who were awake at the time the earthquake occurred reported that the quake was immediately preceded by a dull roar seeming to come from the ground. Shaking is reported to have been nearly continuous for an hour or more after the major shock.

Macdonald was driving through Naalehu, 36 miles from the epicenter, when the earthquake occurred. The car swerved violently, as though it had struck a mudhole. Immediately afterward branches started to snap from trees overhead and fall on the pavement.

Within a matter of moments several houses, churches, and a school building were badly damaged, many other houses slightly damaged, about 200 water tanks destroyed, many miles of stone wall thrown down, roads partly blocked by rock slides, road pavement and shoulders badly cracked, cemeteries damaged, telephone communication and electric power supplies disrupted. Fortunately, only two persons were injured, and they not seriously.

Damage extended for more than 50 miles along the highway that encircles the island, from Holualoa on the north to Honuapo on the southeast. Damage was greatest along the 10-mile stretch from the village of Captain Cook to Hookena (Fig. 1), but as far away as Naalehu many dishes were thrown to the floor in homes, groceries and liquor bottles thrown from shelves in stores, and one house was shifted several inches on its foundations. A few objects were toppled from shelves, pavements were cracked, and numerous landslides started in the vicinity of Kilauea Caldera, 45 miles from the epicenter.

At Napoopoo the ocean was observed withdrawing from shore, and most of the inhabitants of the village were hurriedly evacuated to higher ground until the possibility of a destructive tsunami was past.

Two small fires broke out. One was at Kaimalino, 0.3 mile south of Kealia, where kerosene, spilled in a kerosene-powered refrigerator, caught fire. The other was in Naalehu, where the earthquake upset a kerosene lamp. Both fires were quickly extinguished.

Bright flashes of white light at the time of the major earthquake were reported by persons at Naalehu and Pahala. These persons believe the flashes were not the result of electrical short circuits. Peculiar lights have occasionally been reported during other strong earthquakes.

During the night of August 21–22 persons in the central Kona area reported a distinct odor of hydrogen sulfide, apparently occurring in intermittent waves. The source of this odor is not known. No increase of fuming was observed at the vents of the 1950 eruption on the southwest rift of Mauna Loa.

Aftershocks in great number followed the major earthquake. The seismograph at Konawaena School was badly damaged by the first quake, so the total number of aftershocks will never be known. However, Mrs. H. Masuhara, at Keei, counted 109 felt earthquakes between the principal shock and nine o'clock the next morning. The Konawaena seismograph was repaired and restored to operation at 15:15 on August 23. It recorded 90 earthquakes during the next 24 hours and 494 earthquakes up to midnight on August 31. Most of these, of course, were too small to be felt, even close to the epicenter. Strong aftershocks occurred at 01:28, 09:56, 10:12, 18:32, and 22:48 (Hawaiian Standard time) on August 21, and at 17:15 on August 22. Only slightly less strong were those at 02:14 and 06:28 on August 22. Because of continued earthquakes, graduation ceremonies at Konawaena School on August 22 were held outdoors instead of in the auditorium.

INSTRUMENTAL DATA

The major earthquake dismantled all seismographs on the island of Hawaii. All but the Bosch-Omori seismograph in the Whitney Laboratory on the northeast rim of Kilauea

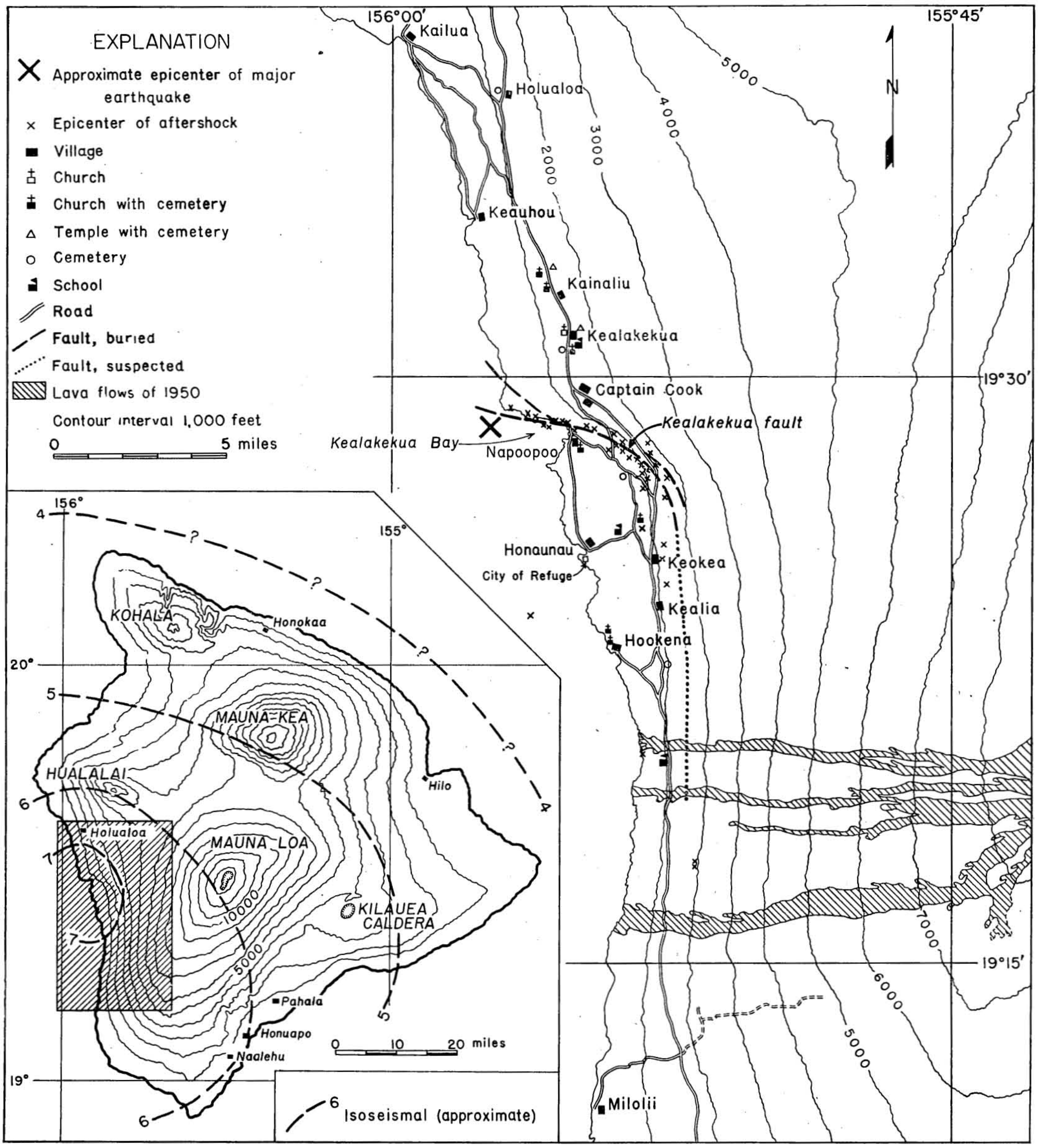

FIG. 1. Map of the central Kona district showing the location of places mentioned in the text and the approximate locations of the epicenters of the major earthquake of August 21, 1951, and of the aftershocks for which reasonably good locations were obtained. The inset map of the island of Hawaii shows the location of the area (shaded) covered by the other map and the approximate position of the isoseismal lines for the major earthquake.

Caldera were dismantled by the preliminary waves. Precise time control and, consequently, the precise time of arrival of the first waves are lacking on the Kona and Hilo instruments. As a result, instrumental data are inadequate for the close location of the focus of the earthquake. The duration of the preliminary waves on the north-south component of the Bosch-Omori instrument was 9.5 seconds, corresponding with a distance of approximately 47 miles from the Whitney Laboratory to the origin of the quake.

John C. Forbes, instrument maker at the Volcano Observatory, repaired the minor damage to the Bosch-Omori seismograph and put it back in operation at 01:24, 27 minutes after the first earthquake started. At that time the instrument was recording the long waves of a large earthquake. The period of these waves ranged from about 6 to 8 seconds and averaged approximately 6.7 seconds. Their maximum double amplitude was 67 millimeters, corresponding to a theoretical ground displacement of approximately 0.5 millimeter. These waves continued with gradually decreasing amplitude until 03:20. Because no other earthquake at an appropriate time was observed by more distant stations, it is believed that these long-period waves were the surface waves of the major Kona earthquake.

The time of origin of the major earthquake is given in the notice of preliminary determination of epicenter issued by the U. S. Coast and Geodetic Survey as $00^h56^m57.5^s$ Hawaiian Standard time ($10^h56^m57.5^s$ Greenwich Civil time). The time of beginning of registration of the preliminary waves at the Whitney Laboratory at Kilauea was 00^h57^m 09.5^s Hawaiian Standard time.

The direction of the first ground movement at Kilauea Caldera was east-southeast and up, that at the Mauna Loa station was east-northeast, and that at the Kealakekua station was east-northeast. At the Kealakekua station the north-south component was only slightly damaged, but on the east-west component the suspensions were broken and the weight dropped on the floor 2 feet west of the pier.

The Kona seismograph, at Konawaena School (Fig. 1), was restored to operation at 15:15 on August 23. Previous to that time, location of the points of origin of the aftershocks on an instrumental basis was uncertain because of the very short base of the triangle formed by the intersection of lines from the earthquake foci to the other stations. Earthquakes after that time are fairly well located because of the control given by the Kealakekua seismograph. Most of these were located by means of data from four stations: Kealakekua, Mauna Loa, Hilo, and Whitney (Kilauea).

Locations of the epicenters of aftershocks which occurred after 15:15 on August 23 with serial number greater than 190 are shown in Figure 1. Thirty-three such aftershocks have been located with small probable error. Most of them fall on or close to a fault that runs out to sea in a west-northwesterly direction along the northern edge of Kealakekua Bay. The existence of this fault, partly buried by later lava flows, has been recognized for many years (Dana, 1890: 30; Stearns and Macdonald, 1946: 37, pl. 1). At its eastern end it bends southward, and the writers have suspected that the abnormally steep lower western slope of Mauna Loa inland from the highway for 15 miles or more south of Captain Cook is a fault scarp deeply buried by later lava flows. An interesting partial confirmation of this theory is furnished by the location of the epicenters of several aftershocks along this line (Fig. 1).

The frequency of aftershocks decreased rapidly from August 23 to September 4. As is shown in Figure 2, the average frequency then decreased very slowly until the end of September. No figure is available for September 7 because of mechanical failure in the recorder at the Kealakekua station. The apparent depth of origin of the aftershocks ranged from 3 to 12 miles, most being about 6 or 7 miles. No progressive change of depth with passage of time is apparent.

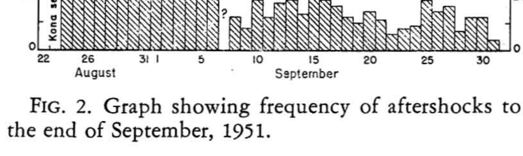

FIG. 2. Graph showing frequency of aftershocks to the end of September, 1951.

Altogether, from the time it was put back in operation until the end of August, the Kealakekua seismograph recorded 494 earthquakes, and until the end of September 965 earthquakes. Nearly all of these are regarded as aftershocks of the big earthquake of August 21. Most were too small and shallow-seated to be recorded at the other stations, hence their foci could not be closely located. It appears certain, however, that most originated along the Kealakekua fault at the northern edge of the Kealakekua embayment.

EFFECTS OF THE EARTHQUAKE

Description of Terrane

The epicentral area lies on the western slope of Mauna Loa, a few miles south of the surficial boundary between Mauna Loa and Hualalai Volcanoes. It is transversed from north to south at altitudes of 1,000 to 1,300 feet above sea level by the main highway, from which roads lead to the shore at Napoopoo, Honaunau, Hookena, and Milolii (Fig. 1). In the vicinity of the highway the average slope of the land surface is about 10 degrees, which is several degrees steeper than the average for Mauna Loa slopes in general. Above an altitude of 5,000 feet the average slope decreases to about 7 degrees. The steepness of the lower part of the slope is believed to result from an ancient fault scarp deeply buried by more recent lava flows.

In the area within 6 miles south of Napoopoo the steep zone is narrower and more sharply defined than farther south, and west of it the slope again flattens toward the sea. Three miles east-southeast of Napoopoo the steep zone turns sharply northwestward and becomes even steeper, taking on the unmistakable characteristics of a fault scarp mantled by more recent lava flows. This scarp forms the northern boundary of Kealakekua Bay, and there the older lava beds in the scarp are not mantled by later flows.

The steep seaward slope results in a distinct asymmetry of the terrane, which asymmetry of necessity extends to nearly all structures on the terrane. Buildings rest on foundations that are high on one side and low on the other. Roads in many places rest on a cut on one side and fill on the other, or on a fill which is shallow on one side and deep on the other. Stone walls parallel to the coast have one sloping side shorter than the other. All of this results in a lesser degree of stability than in structures built on level terranes, and in a favored direction of unstability. Partly because of the higher foundations and deeper fills on the seaward side and partly because of the continuous effect of gravity, structures tended to move downhill during the earthquake regardless of the direction of the actual shaking. This effect must be considered in using the direction of displacement of objects as a means of locating the epicenter.

Rock Slides

Many small rock slides in highway cuts were caused by the earthquake. Most of them came from cuts on the inland side of the highway, probably largely because the cuts were higher on that side. Most of the slides were small, bringing down blocks less than 2 feet across. These caused little damage and were easily removed. A few larger slides brought down large blocks weighing several tons, the removal of which required the use of bulldozers or other heavy equipment. The large slide farthest from the epicenter occurred at a high roadcut just west of Honuapo, 40 miles from the epicenter. Small slides and rock falls in road cuts extended all the way to Kilauea Caldera, 44 miles from the epicenter. Many small rock avalanches took place in Halemaumau Crater during and for several days after the earthquake.

A large part of the damage to road cuts did not, strictly speaking, result from sliding of the materials. Most of it was merely a fraying of the banks by the rolling down of loose or semiloose material. Few of the highway cuts exceeded 5 feet in height, and few

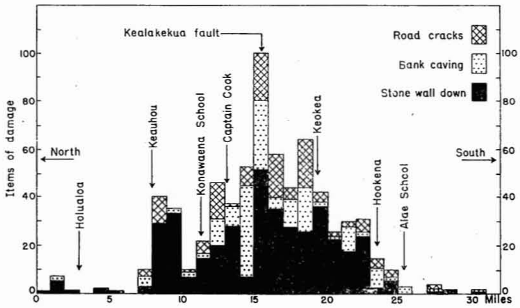

FIG. 3. Diagram showing the frequency distribution of three of the principal types of earthquake damage along the main highway. The arrows indicate the position on the highway of some villages and other features. Note the centering of damage close to the Kealakekua fault.

were dressed back to any approximation to an equilibrium slope. The earthquake of August 21 greatly exceeded in size any previous quake in the affected area since the road cuts were made, and shaking during the earthquake merely dislodged much of the loose material and allowed it to roll down onto the road.

The distribution of abundance of rock slides in road cuts is shown in Figure 3, in which it is represented by the portion of the columns labeled "bank caving." Like the other damage shown in the graph, it was greatest in the immediate vicinity of the Kealakekua fault, inland from and a little south of Kealakekua Bay.

Many large slides took place on the fault scarp at the northern edge of Kealakekua Bay. The slides caused a disturbance of the water of the bay just after the earthquake, and many residents of the coastal village of Napoopoo fled inland, fearing a big tsunami. Slides continued on the Kealakekua cliff for several days after the earthquake, sending up clouds of yellowish-brown dust, leaving fresh scars on the cliff face, and building talus fans at the foot of the cliff.

Less numerous and smaller slides also occurred along the cliff just inland from the village of Hookena Beach. The cliff at Hookena is believed to be an ancient fault scarp, mantled by lava flows from the upper slopes of Mauna Loa during prehistoric times. Many fragments of the lava veneer were shaken down during the earthquake.

Tsunami

Despite early reports to the contrary, there is no doubt that the earthquake was accompanied by a small tsunami, or "tidal wave." At Napoopoo wharf the water was observed to withdraw from shore. The tide was low at the time. Withdrawal of the water lowered the level to about 4 feet below normal low-tide level. Immediately afterward the water returned shoreward, and the level rose about 2 feet above low-tide level.

At Milolii, Eugene Kaupiko reported that a few minutes after the earthquake, which he felt while in a canoe anchored offshore, the water receded from shore, revealing the sea bottom as far out as the edge of the wharf. This represents a lowering of the water level of about 3 feet. After the withdrawal the water returned shoreward, causing a rise of the water level 3 or 4 feet above normal low water and floating away a canoe that had been drawn up on the beach about 2.5 feet above high-tide level. One large fall and rise of the water level appears to have been followed by many small oscillations.

At Honaunau, between Napoopoo and Milolii, Eli Cooper, caretaker of the City of Refuge, went down to the water's edge a few minutes after the earthquake. At that time he could see no signs of disturbance of the water, but a small tsunami could have occurred between the time of the earthquake and his arrival at the strand. At Hookena no tsunami was observed, and there was none large enough to flood the floor of the dock, about 4 feet above normal water level. However, it cannot be said definitely that no small tsunami occurred there.

The Honolulu tide gauge record shows a distinct oscillatory disturbance of the water starting at approximately 01:35, about 38 minutes after the earthquake. Seven or more oscillations are detectable, with an average period of about 14 minutes, reaching an amplitude from crest to trough of 3.6 inches. This undoubtedly is the record of a seiche set up in Honolulu harbor by the tsunami. Using the time of beginning of the disturbance at Honolulu as that of arrival of the tsunami, the average speed of travel of the tsunami from the epicenter to Honolulu was approximately 284 miles an hour. The time of beginning of the disturbance at Honolulu corresponds well with the calculated theoretical arrival time of a tsunami caused by the Kona earthquake, so there can be little doubt the disturbance was of that origin. A similar disturbance is shown on the record of the Hilo tide gauge. The time of beginning of the disturbance at Hilo is less definite, but appears to have been about 02:38. This corresponds with a much slower average speed of travel of the tsunami, of about 78 miles an hour, as the waves were refracted around the island in comparatively shallow water.

Damage to Buildings

Shortly after the earthquake the Kona police estimated that about 200 houses in the area had suffered some degree of damage. Most houses in the area near the epicenter are of frame construction, set on knee-braced timber underpinning. Such supports proved capable of undergoing the shaking and distortion caused by the earthquake without serious damage. Most of the damage was minor and quickly repaired. Some houses shifted from a fraction of an inch to 3 or 4 inches on their foundations. Many were sufficiently twisted out of line to make it difficult or impossible to close windows and doors. In nearly all houses dishes and other objects were thrown from shelves. Only the more seriously damaged structures are enumerated here.

At Kaimalino, 0.3 mile south of Kealia (Fig. 1), a shop building collapsed. This building was placed on timber supports level with the highway in front but 6 feet above ground level in back, without adequate cross bracing.

FIG. 4. Overthrown shop building at Kaimalino, from the south.

Failure of the underpinning allowed the building to tilt backward and slump to the ground (Fig. 4). A similar situation was found at Keokea, 1.2 miles north of Kealia, where a service station building slumped downhill away from the highway and partly collapsed.

In the Kahauloa area, about 1.7 miles east of Napoopoo village, the walls of a store partly collapsed as a result of distortion of the building caused by shifting on its foundation. The warehouse of another store was badly damaged.

At Hookena Beach two old frame houses were destroyed. One, which had been occupied briefly in 1889 by Robert Louis Stevenson, fell when its timber underpinning failed, and collapsed. The other also was dropped onto the ground by collapse of its underpinning. It appears to have fallen almost straight downward. The building was somewhat twisted, but not otherwise seriously damaged. At Kealia and at Kiilae, about 0.4 mile south of Kealia, two other frame houses were badly damaged by collapse of their timber underpinning. All of these cases of collapse of frame houses appear to have been caused by inadequate bracing or poor materials in the underpinning, in some instances probably aggravated by insecure footings.

The cases of structural damage most distant from the epicenter occurred at Naalehu, 36 miles southeast of Napoopoo, where wallboard in a restaurant was cracked, and one

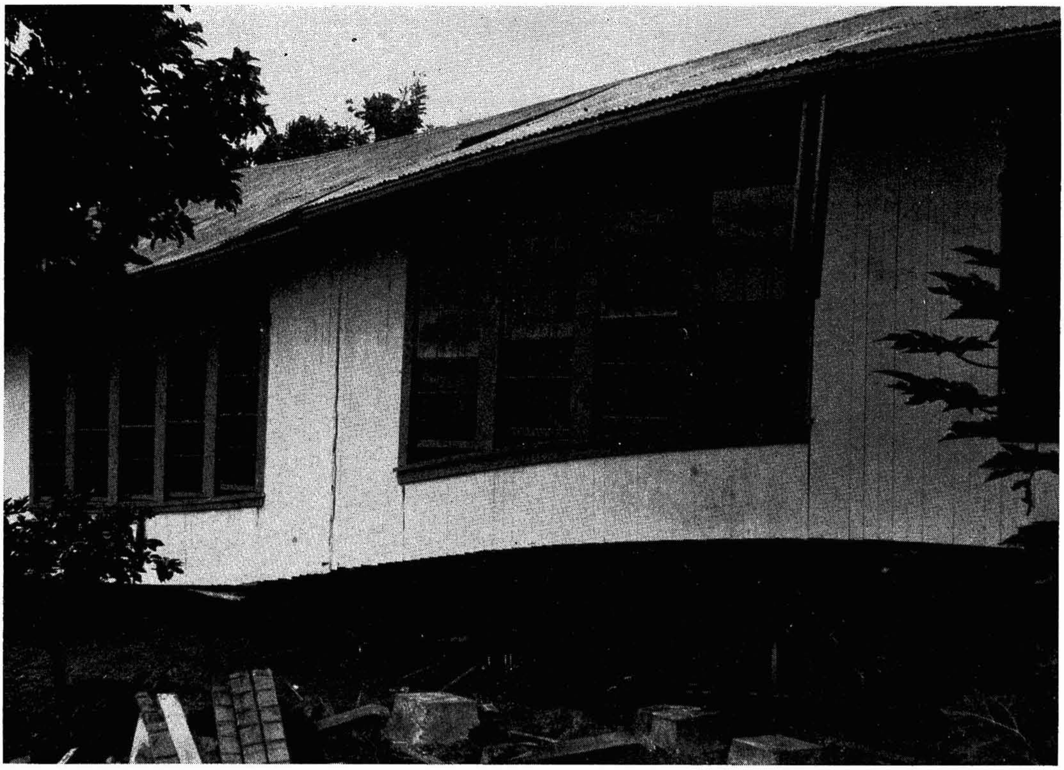

FIG. 5. Central portion of Honaunau School, from the southwest. All but the south end of this building was let down and moved westward owing to inadequate bracing of the underpinning in an east-west direction transverse to the longer dimension of the building.

house was moved several inches on its foundation.

A striking example of the effect of poorly designed underpinning is furnished by the Honaunau School. This was a long, narrow frame building placed with its length parallel to the contour of the ground surface. The front of the building was about 3 feet and the back about 10 feet above ground level. It was supported on timber posts. The posts and knee bracing parallel to the length of the building were entirely adequate, but there was comparatively little bracing parallel to the shorter direction of the building, and some of this was fastened not to joists but to floor boards. As a result, the underpinning was deficient in stiffness in the direction parallel to the ground slope. The direction of shaking during the earthquake was nearly parallel to this direction of weakness in the structure, and the swaying of the structure caused the underpinning to fail in part and to allow the building to slump downhill onto the ground (Fig. 5). The building is considered a total loss.

There were several church buildings with masonry walls in the area near the epicenter. Most of these suffered some damage, and some were very seriously damaged. The masonry consists of fragments of lava rock laid with a mortar made by calcining coral limestone. In some there was very little mortar in the inside parts of the wall. Most of the buildings were more than 95 years old.

The Central Kona Church at Kealakekua suffered cracking of the interior plaster on the east and west walls, but the masonry showed little or no cracking. At the back of the church is a small lean-to addition, the roof of which is supported by beams with one end set into niches in the wall of the main building. During the earthquake there was enough differential movement of the two portions of the building to pull the beams out of their supporting niches and allow the roof of the addition to drop a few inches. At the front of the church is a tower covered with exterior plaster. The tower and main church building are essentially separate structures and appear to have moved independently during the earthquake. The plaster of the tower was badly cracked.

St. Paul's Church at Honalo, 1.9 miles north of Kealakekua, suffered severe cracking of the masonry in both the main building and the rectory. Kahikolu Church, at Napoopoo, suffered surprisingly little damage. The lintels and interior plaster showed some cracking, but the masonry was unharmed.

The Protestant church at Hookena Beach was badly damaged. The building consisted of masonry walls and a sheet-iron roof, supported on heavy handhewn beams which in turn were supported by east-west beams resting in niches on the upper edge of the front and back walls. During the earthquake nearly the whole front (west) wall was thrown out, some debris being as much as 25 feet from

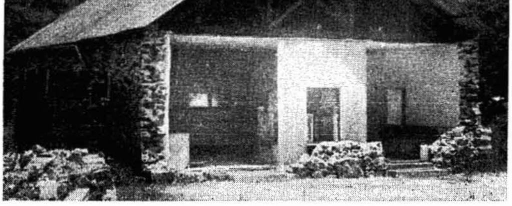

FIG. 6. West end of Pukaana Church at Hookena Beach showing complete demolition of masonry wall of this 100-year-old structure. Much of the debris was cleared away soon after the earthquake. No nearly comparable damage to this building is known to have taken place during the century since it was built.

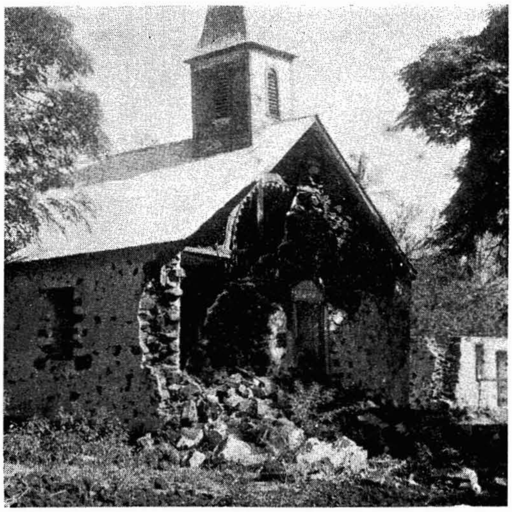

FIG. 7. Catholic Church 0.6 mile north of Hookena Beach, from the northwest. The east end of this church was similarly thrown down and outward, to the east. The near corner and the corresponding corner of the small building, already without a roof, suggest displacement most markedly to the northwest, in the general direction of the epicenter.

the building (Fig. 6). The other walls were not appreciably damaged, even the interior plaster being almost uncracked. It appears possible that during the quake the roof may have tended to move as a separate unit from the rest of the structure and, by its tendency to lag behind during the initial violent eastward movement of the ground, may have pushed out the front wall.

Similarly, a small stone building nearby, which had long been without a roof as is shown by trees growing within the walls, had both its end walls thrown outward, to west and east, while the side walls remain standing though somewhat cracked.

The Catholic church 0.6 mile north of Hookena Beach was very heavily damaged. The upper portions of both the east and west walls were thrown down (Fig. 7), and the interior plaster on all walls was badly cracked. However, the walls were built merely of loose stones laid together without mortar between them except close to the faces, where the interior and exterior plaster had penetrated a short distance. Considering the type of construction, probably the most surprising feature is that the building had not collapsed previously in one of the strong earthquakes which occur in Kona every few years.

The lessons to be learned from the structural damage caused by the earthquake are those which have been taught by many strong earthquakes elsewhere. A large proportion of the damage results from poor construction or from poor or inappropriate materials. Unreinforced masonry structures are inadvisable in any area subject to strong earthquakes. Footings should be firm, and construction materials, particularly the underpinning, should be sound. Cross bracing, particularly of underpinning, should be adequate in all directions. The best insurance against earthquake damage is good construction.

Damage to Water Tanks

Practically all dwellings in the Kona area are equipped with water tanks for storage of rain caught on the roof. Nearly all these tanks were of wooden stave construction. A large number of these round, tub-type tanks were destroyed or damaged by the earthquake.

The few metal and masonry tanks were undamaged. Because of their importance, not only in Kona but in many Hawaiian communities, a special study of damage to these tanks has been undertaken. The results will be published elsewhere. Only a brief summary is given here.

Altogether, approximately 200 tanks of a total of more than 1,000 in the heavily shaken area were damaged or destroyed by the earthquake. Tank damage extended from Keauhou on the north to Milolii on the south and was most severe in the area from Captain Cook to Hookena. Tanks showed all degrees of failure, from the development of slight leaks to complete collapse. A few tanks may, at least in part, have been pushed over by neighboring structures. Thus, the tank at the southern end of the Honaunau School building (Fig. 8) may have been partly pushed westward by the collapse of the adjacent

FIG. 8. Demolished tank west of the south end of Honaunau School, footings on which the tank formerly stood, and part of the school building, from the southwest.

building, to which it was connected by a rigid wooden down-spout. However, most of the damaged tanks appear to have failed because of their own behavior during the earthquake. The commonest features contributing to tank failure appear to have been poor footings and inadequate cross bracing of the underpinning.

Damage to Stone Walls

The loose stone walls characteristic of the Kona area were extensively damaged by the earthquake. The principal damage was in the area between Keauhou, 3.5 miles north of Kealakekua, and Pahoehoe, 3 miles south of Hookena (Fig. 1). However, isolated instances of wall derangement were observed as far north as Honokahau, 16 miles north of the epicentral area, and Naalehu, 36 miles southeast. The distribution of damage to walls is shown graphically in Figure 3. Many miles of wall required rebuilding. Since the cost of contract rebuilding is approximately a dollar a yard, the total monetary loss from the destruction of walls is considerable.

Most of the stone walls in the area consist of irregular fragments of clinkery aa lava less than a foot across. A few walls have bases of blocks a foot or more long reaching half-way or more through the wall, and, especially in the older walls, occasional slabs are laid partly or entirely through the wall to help tie it together. Because of the rough, irregular surfaces of the fragments it is possible to build them into a nearly vertical wall 3 or 4 feet high and only about 30 inches thick at the base. Such walls stand well under ordinary conditions, but, because of the shortness of the bonding surfaces of adjacent blocks, they are rather unstable under any joggling, such as by earthquakes. The earthquake of August 21 caused extensive shaking down of the walls. The commonest type of damage was a slumping of the upper part of the downslope face of the wall, the fragments rolling down and out a short distance from the base of the wall. Such damage was especially common on the north-south trending walls and at high places on the walls. In a few instances, walls on nearly level ground were dislodged almost equally in both directions, but the failure was preponderantly on the west side of the walls, and the material from the walls was displaced westward.

Some of the westward displacement of material probably resulted from the tendency of the loose material composing the wall to lag behind during the initial strong eastward movement of the ground. However, a large proportion, perhaps most, of the failures of the walls on their west side undoubtedly resulted from the fact that, because of the general westward slope of the ground, the west side of the wall was higher and usually steeper than the east side, and there was a tendency for materials to shift downslope under the influence of gravity.

Well-built walls were surprisingly resistant to earthquake damage. Thus, the wall along the landward side of the highway from Honaunau to Napoopoo, built of carefully placed rectangular blocks of lava, was almost wholly undamaged despite its location very close to the epicenter. Likewise, in other parts of the epicentral area, older walls in which slabs extending through a large portion of the wall had been used to tie the wall together showed comparatively little damage.

At the ancient City of Refuge at Honaunau, about 20 feet of the seaward side of the main outer wall of the enclosure collapsed. It is interesting to note that damage was restricted to a reconstructed portion of the wall, whereas the remaining portions of the original enclosure wall and the walls of the heiau platforms were undamaged. Homer Hayes, a close student of the City of Refuge, has made the highly plausible suggestion that the peculiar construction of the ancient walls, in which occasional broad slabs extend entirely or largely through the wall and sometimes bridge open spaces beneath, is responsible for the greater resistance to earthquakes of the old portions of the wall.

Damage to Roads

Damage to paved roads was of three general sorts: (1) cracking of pavement, (2) cracking and slumping of shoulders and separation of shoulders from pavement, and (3) collapse of road cuts, causing partial obstruction of the road. The latter has already been discussed under the heading "Rock Slides." Minor cracking of shoulders occurred over an area extending about 10 miles north and 12 miles south of the approximate epicenter, and a few cracks were formed as far away as the northeast side of Kilauea Caldera, 47 miles from the epicenter. However, extensive pavement cracking and slumping were restricted to the area between Captain Cook and Hookena. The distribution of cracks in the road is shown in Figure 3.

Observed cracking or slumping of the pavement or shoulders was entirely restricted to portions of the road on fills. In building the road, some gullies were crossed by laying in a rock fill having a batter, or departure from vertical, of less than 1 in 4, filling with fine material, and laying asphalt pavement across the top. Such fills were insufficiently stable to withstand the shaking of a strong earthquake, and in several places the down-

FIG. 9. Crack along roadside south of Kealakekua, from the south, showing separation of embankment from edge of pavement due to slumping.

slope face of the fill was dislodged, allowing the material of the road bed to settle, cracking the pavement. In other places the fill appears to have settled a little merely by compaction during the jostling by the earthquake, causing cracks in the pavement.

A common occurrence was the formation of a crack parallel to the edge of the pavement on its downslope side, either within the pavement a few inches from its edge or between it and the shoulder (Fig. 9). Some of these were as much as 75 feet long and 8 inches wide. This appears to have resulted from a downslope lurching of the shoulder, moving as a separate unit from the portion of the fill beneath the pavement. The independence of movement of the shoulder and pavement was interestingly shown along the highway about 2 miles southeast of Captain Cook, where soil and sod on the shoulder were overthrust as much as an inch onto the pavement.

Damage in Cemeteries

Many headstones in cemeteries in the area near the epicenter were deranged by the earthquake. As a part of the general earthquake investigation, these cemeteries were examined, and a rough statistical study of the damage was made. Unfortunately, owing to shortage of personnel and pressure of other duties, we were delayed several days in making the cemetery examinations, and some restoration of headstones had already taken place in some cemeteries before we visited them. However, in most cemeteries little restoration had been done, and the damage remaining was probably a representative sample of the original damage. It is believed that practically all stones which had been dislodged could be detected, even after they had been replaced, by breaks or scratches on the stone or disturbance of the cement bond at the base of the stone.

There are more than 50 cemeteries in the area, but most are small family or church plots with few graves and have not been used in recent times. In some places burial was in vaults without headstones or with headstones or markers firmly cemented in place and not readily susceptible to damage by an earthquake of the intensity of the one under study. Most of the valuable information came from a few of the larger cemeteries. Damage at these is summarized in the accompanying table, and their locations are shown in Figure 1.

Derangement of headstones included overturning of stones and shifting of stones on their bases with or without rotation. In addition many grave caps were broken, some by falling or disturbance of headstones and some by lurching or slumping of the adjacent subsoil. The latter type of damage was particularly prevalent on steep slopes, where the subsoil is thick and loose. Damage of all sorts was restricted to the area between Honalo and Honokua, 5 miles northeast and 10.5 miles south-southeast, respectively, of the probable position of the epicenter.

In cemeteries north of Keauhou no damage or derangement was noted. Two miles south of Keauhou, at Lanakila cemetery in Lehuula, 4 of the 15 headstones were dislodged to the west. Inland and slightly northward, at the Daifukuji Mission in Honalo, about 5 miles

FIG. 10. Gravestone rotated counterclockwise, in Daifukuji cemetery, Kainaliu, looking approximately northwest.

north of Napoopoo, of an estimated total of 150 grave markers, 6 toppled west, 7 north, 2 east, and none south. Six had been shifted north, 16 were twisted counterclockwise, and 2 clockwise; 8 grave caps were broken (Fig. 10). It was reported that many more had been disturbed but had been restored.

At Hongwanji Mission, Kealakekua, with more than 600 graves, 12 headstones were overthrown to the west, 9 to the east, and none to the north or south. Thirty-four were twisted clockwise, 11 counterclockwise, one each shifted north, west, and south; 22 grave caps were broken.

At the Central Kona Church cemetery at Kealakekua, 12 headstones and one large memorial monument were overturned westward and one stone eastward. Another stone was rotated counterclockwise. In the Episcopal cemetery, just across the highway, five headstones were overturned westward, one was rotated counterclockwise, and one clockwise.

At Kahikolu Church, about 0.5 mile south of the Kealakekua fault line, of a total of 10 headstones, 2 were overturned to the west and one was twisted clockwise. Two miles farther inland but only about 0.6 mile south of the fault line is another cemetery of the Hongwanji Mission. Here, of more than 200 headstones, 29 were still down on September 7, the majority having been dislodged to the west, and 10 or more had been replaced. Thirteen had been twisted clockwise and 4 counterclockwise; 24 grave caps were broken. There was much damage to caps and markers in the lower section of the cemetery where the ground is composed of rocky talus.

At St. Benedict Church, 1.5 miles farther south, there is a cemetery with approximately 100 markers. Nearly half of these are wooden crosses, which were not deranged. Several others are light concrete crosses with wire reinforcing. Some of these were broken at the shank so as to expose the wires one or two of which were the sole remaining support. Of about 20 vertical headstones, 11 were displaced or broken.

The most complete derangement of gravestones was found in the Kalahiki Japanese cemetery, a small hillside cemetery 3.8 miles south of Kealia, where only 2 of 30 markers were found in position 5 days after the earthquake (Fig. 11). The dislodgement was chiefly to the southwest and, to a lesser extent, to the northeast. Ten were shifted to the north without being thrown down. Seven, including some of these 10, were rotated clockwise and one counterclockwise. Here, on loose, steeply sloping ground, a large proportion of the grave caps were broken, owing to poor design and to construction on the newly heaped grave mound. This cemetery is about 11 miles south of the probable epicenter. South of this point no cemeteries with headstones susceptible to overturning or rotation were found.

The prevailing east-west azimuth of fall of gravestones throughout the area is probably largely the result of the prevailing westward slope. The orientation of most cemeteries is governed by the general north-south alignment of the principal roads, and, in turn, most gravestones face the west or east and have

TABLE 1
SUMMARY OF DAMAGE IN CEMETERIES IN AREA EXAMINED

NAME	LOCATION	DISTANCE AND DIRECTION FROM NAPOOPOO		APPROXIMATE NUMBER OF HEADSTONES	HEADSTONES OVERTURNED						HEADSTONES ROTATED	
					NUMBER	PER CENT	APPROXIMATE DIRECTION				CLOCKWISE	COUNTER-CLOCKWISE
							N	E	S	W		
		miles										
Holualoa Japanese	Holualoa	10	N	300	0	0	0	0	0	0	0	0
Daifukuji	Honalo	5	N	150	15	10	7	2	0	6	2	16
Lanakila Church	Kainaliu	4.5	N	12	4	33	0	0	0	4	0	0
Hongwanji Mission	Kealakekua	3	N	600	21	3.5	0	9	0	12	33	10
Central Kona Church	Kealakekua	2.5	N	30	12	40	1	0	0	11	0	1
Christ Church	Kealakekua	2.5	N	60	8	13	0	3	0	5	1	1
Kahikolu Church	Napoopoo	0.5	S	10	2	20	0	1	0	1	1	0
Hongwanji Mission	Keei	1.5	SE	200	40	20	3	22	1	14	13	4
St. Benedict Church	Honaunau	3.5	SE	100	11	11	0	0	0	11	0	0
Japanese	Kalahiki	7.5	S	31	20	64	1	6	1	12	14	1

FIG. 11. Broken bases, displaced base stones, and overturned headstones in Kalahiki Japanese cemetery, south of Kealia, looking southeast. Partly because of unstable hillside ground and partly because of proximity to the epicenter, damage in this cemetery was widespread and severe; scarcely a grave escaped marked derangement.

the long dimension of their base oriented north-south. Therefore, the stones rock in an east-west direction much more easily than in any other, and, consequently, the most likely azimuth of fall is east-west. Furthermore, under sustained shaking, there is a tendency for all loose objects, including the soil cover, to work downslope to the west under the influence of gravity.

Rotation of Columns

Imamura (1937: 96) has shown that the direction of rotation of short rectangular columns, such as many headstones are, can be useful in determining the direction of motion during an earthquake and, consequently, the approximate azimuth of the line toward the epicenter. If the earthquake motion is parallel to the sides or to the diagonal (A—B, inset, Fig. 12) of the column, rotation probably will not occur. However, if the earthquake motion is in some intermediate direction, such as E—E′ in Figure 12, a rocking of the column will be accompanied by a rotational tendency. A ground motion in the direction E′ will cause the column to rock on the corner B. At the same time, the resultant of the force E′ in the direction CD will tend to rotate the column about the corner B in a counterclockwise direction. Similarly, a motion in the direction E will tend to cause a counterclockwise rotation about corner A. Directions of earthquake motion lying in the unshaded octants of the diagram tend to cause counterclockwise rotation of the column, and directions of motion in the shaded octants tend to cause clockwise rotation.

However, this law of rotation can be, and commonly is, upset by other conditions. Inhomogeneity of the terrane may cause the principal motion to be, locally, in a direction other than the azimuth pointing directly to the epicenter. Also, excentric irregularities in the bottom of the monument or its underlying base, or in the adhesion between the monument and its base, may result in rotation around those irregularities independent of the rotation described above.

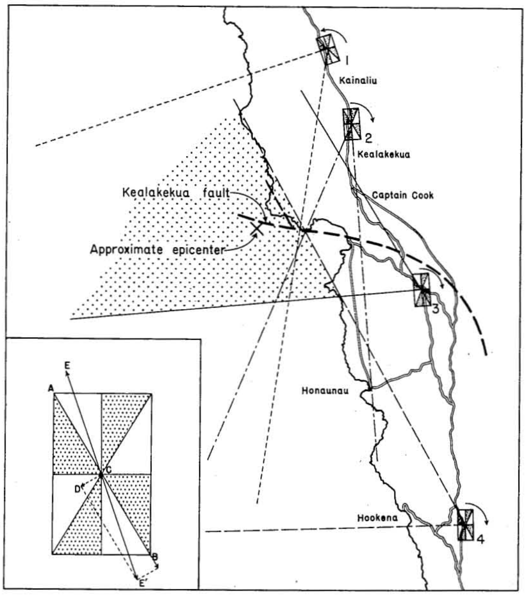

FIG. 12. Map of the central Kona area, showing the prevalent direction of rotation of monuments in cemeteries. The cemeteries are: 1, Daifukuji, Honalo; 2, Hongwanji Mission, Kealakekua; 3, Hongwanji Mission, Keei; 4, Kalahiki Japanese. At each cemetery the arrow indicates the prevalent direction of rotation. The boundaries of the octants containing the direction toward the epicenter are prolonged. The stippled area west of Captain Cook is that in which three or more of the octants overlap. The inset in the lower left is a diagram (after Imamura, 1937) of a horizontal cross section of a rectangular column, indicating the manner in which horizontal earthquake motion E—E′ causes rotation of the column.

During this study it soon became evident that, to be of value, the direction of rotation must be considered on a statistical basis. Thus, two columns only 10 feet apart in the Christ Church cemetery at Kealakekua were rotated approximately equal amounts in opposite directions. However, by using the prevailing direction of rotation of a number of columns in a single area, more useful results were obtained. The average direction of rotation of monuments in each of six cemetery areas from 5 miles north to 10 miles south of Napoopoo were all consistent with an origin of the earthquake on or near the Kealakekua fault from 2.5 to 5 miles west of Napoopoo.

Cemeteries close to the epicenter showed less consistency in the direction of rotation than did those farther away.

In Figure 12 the prevalent directions of rotation of monuments in four cemeteries are shown. Four other cemeteries were omitted because no monuments were rotated in them, or because the number of rotated monuments was too small to yield a reliable statistical result. At each of the four cemeteries plotted, the boundaries of the octants containing the direction toward the epicenter are prolonged. In an area largely west of the shoreline, from 2 miles south to 2 miles north of the approximate trace of the Kealakekua fault, three or more of the four significant octants overlap, and it is within this area of overlap that the epicenter should be situated.

LOCATION OF THE EPICENTER

Because of the dismantling of all but one of the seismographs on the island of Hawaii during the preliminary phase of the earthquake, it is not possible to locate the origin or epicenter instrumentally. The only instrumental datum available is the S—P interval of 9.5 seconds given by the Bosch-Omori seismograph at the northeast rim of Kilauea Caldera (Fig. 13). Using the travel times given by Byerly (1942: 210), this gives a distance of origin of the earthquake of approximately 47 miles from the Bosch-Omori instrument. These curves were derived for sedimentary and granitic rocks but, over a period of several years of use at the Volcano Observatory, have yielded more satisfactory and reasonable earthquake locations than any others. The use of Jones's (1935: 50) curve for duration of the preliminary waves (T*) increases the distance to only 49 miles. Taking into consideration the area of greatest intensity of the earthquake, these distances place the origin of the quake 3 to 5 miles west of the coastline in the vicinity of Napoopoo. The depth of origin appears probably to have been between 5 and 10 miles.

Some information bearing on the location of the epicenter can be derived from the study of damage by the earthquake. The general distribution of damage to roads, stone walls, and road cuts along the main highway is shown in Figure 3. This is based on a count checked against odometer mileage, assigning one unit of damage for each 1 to 15 feet of collapsed wall or road cut. Despite irregularities, the graph shows a distinctly symmetrical, bell-shaped distribution curve, with its peak about 2.5 miles by road southeast of Captain Cook. An average of more than 60 items of damage per mile in the central 5 miles decreases to only one or two per mile more than 9 miles from the center. This point of maximum damage coincides closely with the position of the buried inland extension of the Kealakekua fault. Other types of damage also were most abundant in the same general area. Together with the fact that most of the aftershocks, located by instrumental means, originated on the Kealakekua fault, it leaves little question that the origin of the major earthquake lay on or close to this fault, and that the earthquake almost certainly resulted from movement on it.

The greatest structural damage was farther south, at Hookena, where the destruction of the east and west walls of the two stone churches suggests an epicenter somewhat farther south. The possibility of a twin earthquake with one epicenter lying offshore nearly west of Hookena has been considered, but no other evidence suggests it, and no signs of a second earthquake could be detected from the seismograms either from the island of Hawaii stations or from that of the Coast and Geodetic Survey at Barbers Point on Oahu.

Throughout the Kona area, the prevalent direction of fall of rock slides, stone walls, and tombstones was westward, and the next commonest direction was eastward. The seismograms indicate that the first movement of the ground was eastward, and it is probable that some of the westward fall of objects was

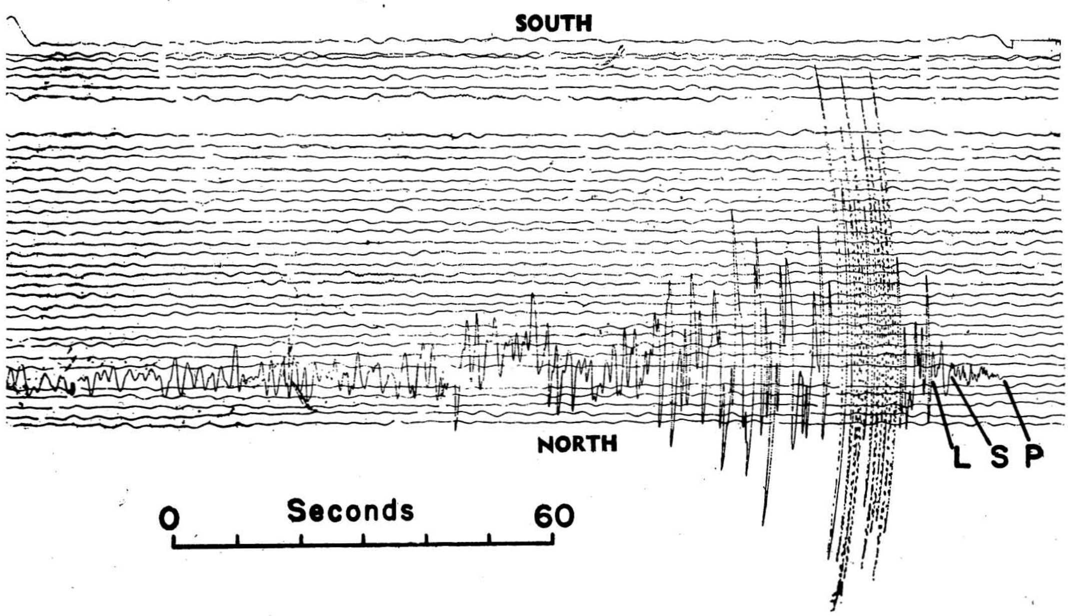

FIG. 13. Seismogram of aftershock recorded at 18:32, August 21, on the Bosch-Omori seismograph at Kilauea. Letters indicate the points of arrival of primary (P), secondary (S), and long (L) waves. The amplitude of 80 mm. on the seismogram corresponds to approximately 0.7 mm. of ground motion at Kilauea, 47 miles from the epicenter.

the result of lagging behind as the ground moved eastward under them. To some extent also, the general east-west azimuth of fall undoubtedly reflects the direction of the epicenter. However, the prevailing east-west slope appears to have been still more important in determining the direction of fall of objects. Its effects on various types of damage have already been indicated.

It has already been pointed out that the prevalent direction of rotation of columns in cemeteries indicates a location of the epicenter within the shaded offshore area in Figure 12. This area contains the seaward extension of the Kealakekua fault.

As a result of the consideration of all lines of evidence, the probable epicenter of the earthquake is placed approximately 3 miles west of Napoopoo, at latitude 19°29′ N, longitude 155°58′ W.

INTENSITY OF THE EARTHQUAKE

There are in common use two different methods of determining and expressing the strength of an earthquake. The older method is based on the observed effects of the earthquake on structures and various other objects. Based on these effects, a numerical value is assigned which is termed the intensity of the earthquake at any one point. Obviously, since the effects are less at greater distances from the origin of the quake, the intensity decreases away from the epicenter. Various scales of intensity have been proposed. That used in the present study is the modified Mercalli intensity scale of 1931 (Wood and Neumann, 1931), in which values range from 1, at which the earthquake is not felt except by a very few persons under especially favorable conditions, to 12, at which damage is total. The second method assigns a value called magnitude to the earthquake, based on the effect on standard seismographs at known distances from the origin of the quake (Richter, 1935). The magnitude is a measure of the amount of energy in the earthquake at its point of origin and, consequently, should be essentially the same at all measuring stations.

The notice of preliminary determination of epicenter issued by the Coast and Geodetic Survey lists the magnitude of the earthquake of August 21 as 6.75 as determined at Pasadena and 7.0 as determined at Berkeley, in California.

Field studies of the effects of the earthquake indicate an intensity of 7 on the modified Mercalli scale in the area near the epicenter, decreasing to 6 at Waiohinu and Naalehu, 5 in the vicinity of Kilauea Caldera and in Hilo, and 4 at Honokaa and in the Kohala district at the north end of the island. At Honolulu, 180 miles (288 km.) from the epicenter, the intensity was 2. Populated areas of the island of Hawaii are largely restricted to the periphery of the island. The interior portions of the island are almost wholly unpopulated, making it impossible to draw accurate isoseismal lines. Approximate isoseismals are shown in Figure 1.

Given a single impulse, the minimum horizontal acceleration that can cause the sliding of a short stone column on a stone base is 71 per cent of the value of gravity, decreasing to 57 per cent at an angle of emergence of 35° to the horizontal (Imamura, 1937: 105). Because the sliding of headstones and, especially, base plates was common in cemeteries during the August 21 earthquake, it might be concluded that the acceleration during the earthquake was at least six tenths that of gravity. However, Imamura (1937: 106) also has shown that small, short-period vibrations in the epicentral areas of strong earthquakes, although they do not themselves cause the displacement of objects, may so lower the normal values of the coefficients of friction that sliding can be caused by longer period vibrations with accelerations much less than six tenths that of gravity. The presence of such vibrations in the Kona area is suggested by local vagaries of displacement and by other behavior. The acceleration which caused the lateral displacement of objects during the Kona earthquake is not known but probably was much less than six tenths that of gravity.

CONCLUSION

The earthquake of August 21, 1951, like most of its aftershocks, probably was caused by movement on the Kealakekua fault. This is one of a number of similar faults along which the lower slopes of Mauna Loa and Kilauea Volcanoes have moved relatively downward and outward toward the deep ocean. In this sense the earthquake was tectonic in origin.

In one sense, of course, all earthquakes in Hawaii are volcanic in origin. However, the August 21 earthquake cannot be directly related to any specific volcanic episode. It is possible that it is related in some way to the great extravasation of lava during the 1950 eruption of Mauna Loa, but there is no evidence to demonstrate such a relationship. On September 16 a series of smaller earthquakes originated on the Kaoiki fault system, a series of fractures corresponding to the Kealakekua fault, on the southeast slope of Mauna Loa. From mid-May until early July abnormally rapid eastward tilting at Kilauea Caldera indicated a tumescence of Mauna Loa Volcano. There is a possibility that both the August 21 earthquake and its aftershocks and the September 16 earthquakes were caused by a slight upward movement of the central portion of Mauna Loa in relation to the lower slopes. The August 21 earthquake has no known connection with any coming volcanic activity, though such a relationship may yet appear.

The southern part of the island of Hawaii is subject to frequent earthquakes, but few are as intense as that of August 21, 1951. The great earthquake of April 2, 1868, judging from the descriptions of damage, was much more severe. Wood (1914) assigned to it an intensity of 10. Its epicenter was farther south, near Waiohinu in Kau, where extensive surface faulting took place. The earthquakes of March 28 and April 3, 1868, also were probably at least as severe as that of August, 1951. The earthquake of October 6, 1929, centered beneath Hualalai Volcano, had a magnitude of 6.5 (Gutenberg and Richter, 1949: 207), and caused damage as far south as Captain Cook. The Maui earthquake on January 23, 1938, had a magnitude of 6.75, about the same as that assigned by the California Institute of Technology Seismological Laboratory in Pasadena for the earthquake of August 21, 1951. During the years from 1929 to 1945, Gutenberg and Richter (1949, table 17) list eight earthquakes of magnitude 5 and over which originated in the general Hawaiian area. During the same interval they list 58 earthquakes in California with magnitude of 5 or more and 127 in Japan and Kamchatka. Thus, during those years, California had about seven times as many large earthquakes as the Hawaiian area, and the Japan-Kamchatka area had about 16 times as many. However, there are some areas, such as the northeastern United States, which have far fewer earthquakes than the Hawaiian area.

Based solely on the 1929–1945 interval, the Hawaiian area can expect an average of about one earthquake of magnitude 5 or more every 2 years. However, during the past century, there have been only six earthquakes of intensity comparable to that of August 21, and no other appears to have been quite as severe in central Kona. There is, of course, no assurance that another equally or even more severe earthquake might not occur in that area in much less time than a century. It might occur within the next few months, but, judging from the past, that is quite unlikely.

Well-built structures, with footings of better quality than many of those now found in Kona, will minimize or even eliminate the damage resulting from the lesser earthquakes which the Kona area experiences frequently in common with all the island of Hawaii except the northernmost part. However, it may not be economically feasible to build in such a way as to eliminate damage from the infrequent large earthquakes.

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